A STANDARD OF HIGH FREQUENCY
POWER FACTOR

by

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INTRODUCTION

In recent years the study of the electrical properties of dielectrics at high frequencies has become increasingly important. Among these electrical properties of dielectrics the loss and power factor are among the foremost that must be known in order to correctly select a material for a given application. Whitehead[1] and many others have made extensive studies and have done considerable research in this field of dielectric characteristics.

Various networks and instruments such as the Q Meter,[2] the Twin T Impedance Measuring Network,[3] and the Susceptance Variation Method[4] have been developed which provide a relative measurment of dielectric loss and power factor at high frequency. However, none of these can be properly considered as a standard instrument. The need for a standard of low power factor at high frequencies exists today to take its place along with the low frequency standard developed by Kouwenhoven and Berberich[5] in 1931, in the field of engineering basic standards of measurement.

A study of the problem of developing a standard of low power factor at high frequencies has been made in the Electrical Engineering Department of The Johns Hopkins University. An experimental model of such a standard has been constructed and the results of tests to date indicate that the instrument is at least a prototype of the needed

standard.

The requirements set up as a basis upon which the aforementioned study was made are:

(a) The design of the standard is to be applicable in the one megacycle to thirty megacycle frequency range.

(b) The standard is to be capable of simulating a dielectric over the range of power factors from .002 to .0002 when inserted in a measuring bridge or network.

(c) The design is to be applicable to an instrument which will operate under potentials up to 25 kilovolts.

In addition to the foregoing it is to be pointed out that power factor measuring networks and bridges may be either of the two terminal or three terminal type. The Q Meter[2] and the Twin-T Impedance Measuring Network[3] are examples of the two terminal type, whereas the circuit developed by Dzmianski, Witt, and Chapman[6] is a three terminal network in which the guard electrode applied to the dielectric sample is the only electrode at ground potential.

The experimental standard of power factor that has been completed is designed for use in two terminal type networks and to operate across a potential difference of 5000 volts. The principles involved are applicable to a standard

for use in a three terminal network, and it would merely require a modification to the shielding to permit the experimental standard to be used in this type of power factor measuring circuit.

THEORY AND THE BASIC CIRCUIT OF THE STANDARD

Inasmuch as a dielectric specimen can be most satisfactorily represented as either a series or parallel combination of resistance and capacitance, a combination of these elements was the obvious choice around which to design the circuit.

It is a well known fact that the resistance of a conductor will vary with frequency, due principally to skin effect. To avoid possible error due to variation in resistance, it was decided to base the design of the circuit of the standard upon the assumption that the actual power being dissipated in a resistor could be precisely measured. The accuracy of the standard would be then dependent upon the precision with which power dissipation could be measured rather than upon an assumed accurate knowledge of resistance. A large part of this paper will deal with power dissipating elements for use in standards of power factor, and it will be seen that the decision to employ the more basic quantity, power, eliminates many engineering and design difficulties.

The basic circuit assumed in the study, and that employed in the constructed experimental standard, is shown in Figure 1. All currents are assumed to be root mean square values.

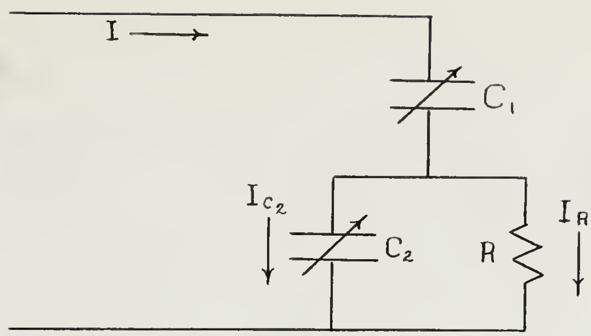

Figure 1

C_1 is a high voltage precision condenser and is the capacitance determining element of the circuit. The power factor of this condenser must be negligible compared to the power factors to be simulated by the circuit as a whole.

R is the power dissipating element, and the aforementioned power that is to be measured will be equal to the square of the current through this branch, I_R^2, times the effective resistance of the element.

C_2 represents a variable array of condensers shunting the power dissipating element. Variation in C_2 will alter the amount of the total current which flows through the power dissipating element and will provide a range of power factors obtainable with one such combination of circuit elements.

Considering the condensers depicted in Figure 1, the specifications for C_1 mentioned above, are met by several precision vacuum condensers commercially available. In

regard to C_2, it was pointed out by Hund[7] that if it is of much higher value of capacity than C_1 the equivalent capacity of the entire circuit is to a very close approximation equal to that of condenser C_1. This is also proven in the next part of this paper. Furthermore, suppose that the equivalent parallel resistance of condensers C_2, is as low as one megohm. This also will have a negligible effect upon the accuracy of the circuit, since the resistance of the dissipating element must be in the order of magnitude of five to ten ohms as is shown in the following section covering a mathematical analysis of the basic circuit. The shunting condenser group therefore, need only to be made up of commercially available condensers of good quality.

The two stray quantities that can affect the circuit of the standard of power factor to such an extent as to make its reliability open to question are stray capacitance shunting C_1, or the entire circuit, and residual inductance. While these quantities can be made negligible by good design and by proper shielding, they will nevertheless be present and their effects must be known. This is particularly true of stray inductance which will cause a variation in the effective equivalent capacity of the circuit with change in frequency. This effect is also considered in more detail in the mathematical analysis, and is seen in the tests of the experimental standard.

MATHEMATICAL ANALYSIS OF THE BASIC CIRCUIT

It is convenient to subdivide the mathematical analysis of the basic circuit of the standard into the two following parts:

A. A study to determine the values of the high voltage capacity, resistance of the power dissipating element, and capacity range of the shunting condenser group to fulfil the requirements of the standard, assuming perfect components and neglecting the effect of stray capacitance and residual inductance.

B. An investigation to determine the effect upon the characteristics of the standard of deviations in the resistance of the power dissipating element and in the capacity of shunting condensers from the values determined by the first part of this analysis. Also in this investigation the stray effects will be considered.

Part A. To facilitate this analysis the foregoing basic circuit, Figure 1, can be mathematically converted into an equivalent parallel circuit. If we set up the expression for the total current, I:

$$I = \frac{E}{Z} = E\left[\frac{1}{\frac{1}{j\omega C_1} + \frac{(R)(\frac{1}{j\omega C_2})}{(R)+(\frac{1}{j\omega C_2})}}\right] \qquad (1)$$

where: E is the root mean square value of the voltage applied to the circuit

R is the ohmic resistance of the power dissipating element

it is only a matter of algebra to rearrange Equation (1) into:

$$I = E\left[\left(\frac{1}{R\left(\frac{C_2}{C_1}+1\right)^2 + \frac{1}{\omega^2 C_1^2 R}}\right) + j\omega\left(\frac{RC_2(1+\frac{C_2}{C_1}) + \frac{1}{\omega^2 C_1 R}}{R\left(\frac{C_2}{C_1}+1\right)^2 + \frac{1}{\omega^2 C_1^2 R}}\right)\right] \qquad (2)$$

or:

$$I = E\,(G + jB) \;=\; E\left(\frac{1}{Req} + j\omega Ceq\right) \qquad (3)$$

where

$$Req \;=\; R\left(\frac{C_2}{C_1} + 1\right)^2 + \frac{1}{\omega^2 C_1^2 R} \qquad (4)$$

$$Ceq \;=\; \frac{RC_2\left(1 + \frac{C_2}{C_1}\right) + \frac{1}{\omega^2 C_1 R}}{R\left(\frac{C_2}{C_1} + 1\right)^2 + \frac{1}{\omega^2 C_1^2 R}} \qquad (5)$$

The standard of power factor can now be represented by a very simple equivalent circuit as shown in Figure 2.

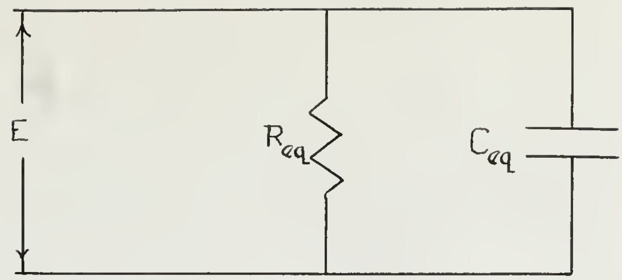

Figure 2

For the above equivalent circuit the expression for the power factor, PF, is

$$PF = \frac{\text{Power}}{\text{Reactive Volt-Amperes}} = \frac{\frac{E^2}{Req}}{E^2 \omega\, Ceq} = \frac{1}{\omega\, Ceq\ Req} \tag{6}$$

Before proceeding let us again examine the requirements of the actual basic circuit. It is necessary to vary the ratio of power to reactive volt-amperes between the limits .002 to .0002 (assume for the instant at one particular frequency) by adjusting the current through the power dissipating element, R, which is in turn accomplished by varying the shunting capacitance, C_2. The magnitude of the total current, I, will be, to a rough approximation, determined by the capacity of the high voltage condenser, C_1. The question then becomes, what are appropriate values of resistance of the power dissipating element and shunting capacity to employ? In particular, what combination will require a satisfactorily small variation in C_2 to obtain the required range of power

factors from the standard?

Let us assume, to obtain an approximation:

$$I = \frac{E}{\frac{1}{j\omega C_1}} = j\omega C_1 E = \text{a constant}$$

This current of magnitude $|I|$ will divide at the junction of R and C_2 (Figure 1) as indicated in the following simple diagram:

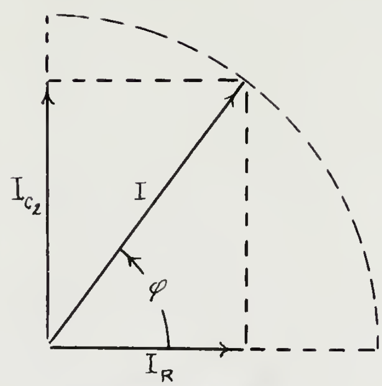

Figure 3

In other words, the vector sum of I_R and I_{C_2} must always be equal to I, the total current, and if this is assumed to be constant the locus of the total current vector, as C_2 is varied from zero to infinity, will be a quarter circle. It is readily seen from Figure 3, that a greater relative decrease in I_R for a given change in I_{C_2} occurs when the angle φ, indicated in Figure 3, is greater than 45 degrees.

If we now assume, continuing the foregoing

approximation, that at a power factor of .002 for the standard:

$$|I_R| = |I_{C_2}| = \frac{|I|}{\sqrt{2}} \quad (\text{i.e., } \varphi = 45^\circ)$$

we can solve for an approximate relationship involving the frequency, the resistance of the power dissipating element, the capacity of the high voltage condenser, and the power factor value of .002.

$$PF \approx \frac{(\,|I_R|\,)^2 R}{|I|\;E} = \frac{\left(\frac{|I|}{\sqrt{2}}\right)^2 R}{(\,|I|\,)^2 \frac{1}{\omega C_1}} = \tfrac{1}{2} R\omega C_1 = .002$$

or

$$R = \frac{.004}{\omega C_1} \tag{7}$$

also, continuing the foregoing assumption:

$$R = |X_{C_2}| = \frac{1}{\omega C_2}$$

from which is obtained the following expression for the desirable lower limit of shunting capacitance, C_2, at the assumed frequency:

$$C_2 = \frac{1}{\omega R} \tag{8}$$

The foregoing simplified calculations and Equations (7) and (8) assume a determined value of the capacity of the high voltage condenser, C_1, and a specific frequency of operation of the standard of power factor. The capacity of the high voltage condenser C_1 must be small for the practical

reason of limiting the total current that will flow through the instrument. Assuming a different frequency would obviously change the results of any preliminary calculations employing the above equations. Rather than continue any discussion of this matter, it is believed that the utility of the Equations (7) and (8) as "starting points" will become apparent in the following procedure used in making the design graph for the experimental standard of power factor.

Inasmuch as a satisfactory condenser was available for use as the high voltage condenser with a lower limit of capacity of less than six micromicro farads this value was assumed for C_1. A frequency of 20 megacycles was selected as what might be termed "the center design frequency" for the standard. Substituting these values into Equations (7) and (8) the following values for the resistance of the power dissipating element and for the lower limit of the shunting capacitance were obtained:

$$R = 5.3 \text{ ohms}$$

$$C_2 = 1500 \text{ micromicrofarads}$$

With the above value of resistance and assuming values of shunting capacitance ranging upward from 1500 micromicrofarads the data shown in Table I was obtained by computations employing Equations (4), (5) and (6) and:

$$\text{Power} = \frac{E^2}{Req} \qquad (9)$$

where E, the voltage across which it was decided to operate the experimental standard, is 3000 volts.

Table I

Design Calculations for the Experimental Standard of High Frequency Power Factor

C_1 = 6 micromicrofarads

R = 5.3 ohms

E = 3000 volts R.M.S.

Frequency = 10 megacycles

$C_2(\mu\mu f)$	Power (Watts)	Power Factor
1500	6.78	.001597
2500	3.99	.00118
3500	2.87	.000847
4500	2.09	.000616
5500	1.55	.000458

Frequency = 20 megacycles

1500	13.5	.00199
2500	7.17	.00106
3000	4.2	.00062
4500	3.71	.0004
5500	2.01	.000277

Frequency = 30 megacycles

1500	18.7	.00184
2500	8.4	.000826
3000	4.6	.000453
4500	2.87	.000282
5500	1.95	.000192

Frequency = 5 megacycles
C_2 = 1500 micromicrofarads

C_1 ($\mu\mu f$)	Power (Watts)	Power Factor
6	1.59	.00094
10	4.45	.00157
15	9.97	.00245

The above data are plotted on the design graph for the standard, Figure 4. A study of the graph shows that with the chosen value of the resistance of the power dissipating element, and with a small extension of the range of shunting capacitance, C_2, the standard ideally could be expected to fulfil the requirements over the 20 to 30 megacycle frequency range with the high voltage condenser set at six micromicrofarads (Curves 1 and 2). Furthermore the graph indicates that the power factor requirements would be partially met at lower frequencies by including in the operation of the standard a provided for variation in the capacity of the high voltage condenser. (Curve 4).

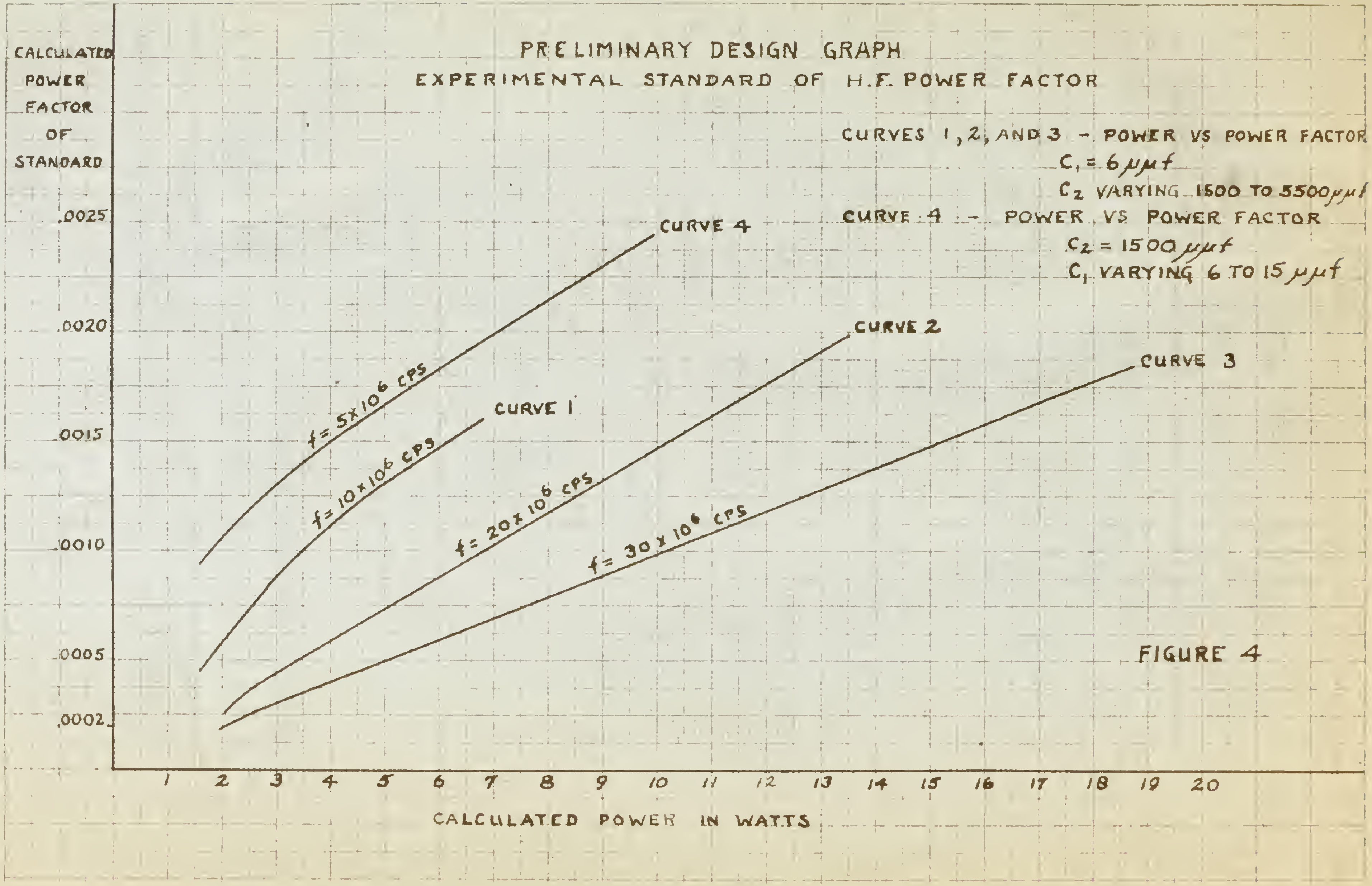
PRELIMINARY DESIGN GRAPH
EXPERIMENTAL STANDARD OF H.F. POWER FACTOR
CURVES 1, 2, AND 3 - POWER VS POWER FACTOR
$C_1 = 6\ \mu\mu f$
C_2 VARYING 1500 TO 5500 $\mu\mu f$
CURVE 4 - POWER VS POWER FACTOR
$C_2 = 1500\ \mu\mu f$
C_1 VARYING 6 TO 15 $\mu\mu f$
CALCULATED POWER FACTOR OF STANDARD
.0025
.0020
.0015
.0010
.0005
.0002
CURVE 4
$f = 5 \times 10^6$ CPS
CURVE 1
$f = 10 \times 10^6$ CPS
CURVE 2
$f = 20 \times 10^6$ CPS
CURVE 3
$f = 30 \times 10^6$ CPS
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
CALCULATED POWER IN WATTS

FIGURE 4

It is to be pointed out that the foregoing study was made for the sole purpose of determining suitable values of circuit components with which to construct the experimental standard of power factor. Perfect, unvarying, resistance of the power dissipating element was assumed and stray quantities were neglected. Neither the above assumption, nor ignoring stray capacitance and residual inductance, is justified in a complete or satisfactory analysis.

Part B. To begin this part of the mathematical study, which deals with the effect of variations in values of circuit components and stray quantities, it is necessary to consider again Equations (4), (5) and (9) from the viewpoint of the actual operation of the standard.

$$Req = R\left(\frac{C_2}{C_1} + 1\right)^2 + \frac{1}{\omega^2 C_1^2 R} \qquad (4)$$

$$Ceq = \frac{RC_2\left(1 + \frac{C_2}{C_1}\right) + \frac{1}{\omega^2 C_1 R}}{R\left(\frac{C_2}{C_1} + 1\right)^2 + \frac{1}{\omega^2 C_1^2 R}} \qquad (5)$$

$$Power = \frac{E^2}{Req} \qquad (9)$$

The power being dissipated by the standard, specified by Equation (9), is a physically measured quantity, and will be known with an accuracy dependent upon the precision of the power measuring technique employed with the power dissipating

element. We can therefore conclude that insofar as the power is concerned any change in actual power dissipated due to variations in circuit parameters will not be a source of inherent instrument error.

Examination of Equation (10), given below, which is the operating equation of the standard, points immediately to the line of investigation that must be carried out.

$$\text{Power Factor} = \frac{\text{Measured Power}}{E^2 \omega \, Ceff} \qquad (10)$$

where Ceff is the actual measured value of the equivalent capacity of the circuit, which we will assume for the time being is identical to Ceq.

It is clearly evident that insofar as the accuracy of the standard of power factor is concerned, the equivalent capacity, Ceff, (or Ceq) is the determining factor. We must first therefore, carefully examine the effect upon the equivalent circuit capacity of variations in power dissipating element resistance and in the shunting capacity. It is to be recalled that the high voltage condenser, C_1, must be of high precision and with negligible conductance, which was a basic assumption.

Values of the equivalent capacity of the circuit, assuming wide variations in the aforementioned parameters, have been calculated using Equation (5), and the results are

shown in Table II, below:

Table II

Calculated Equivalent Capacity of the Experimental Standard of High Frequency Power Factor

C_1 = 6 micromicrofarads

ω = frequency in radians per second

R = resistance assumed for the power dissipating element in ohms

Tabulated values for Ceq are in micromicrofarads

C_2 = 1200 micromicrofarads

ω \ R	5	20	50
30×10^6	5.99955	5.98974	5.97713
60×10^6	5.99654	5.97979	5.97226
90×10^6	5.99321	5.97537	5.97113
180×10^6	5.98645	5.97296	5.97054

C_2 - 3600 micromicrofarads

ω \ R	5	20	50
30×10^6	5.99849	5.99292	5.99035
60×10^6	5.99462	5.99052	5.99010
90×10^6	5.99277	5.99025	5.99005
180×10^6	5.99153	5.98987	5.99000

C_2 - 6000 micromicrofarads

30×10^6	5.99731	5.99443	5.99408
60×10^6	5.99543	5.99412	5.99402
90×10^6	5.99472	5.99405	5.99401
180×10^6	5.99365	5.99401	5.99399

This tabulation shows that the difference between the equivalent capacity of the circuit and the capacity of the high voltage condenser is extremely small over wide variations in power dissipating element resistance, frequency, and capacity of shunting condenser. Differences are so small in fact that an extremely accurate method of equivalent capacity calibration of the standard would be necessary to make them detectable from an average value.

If the high voltage condenser, C_1, is shunted by stray capacity, or if there is stray capacity shunting the entire circuit it is evident that this stray capacity will be directly additive to the foregoing calculated values of circuit equivalent capacity. This will obviously cause the characteristics of the instrument to depart from those indicated by the design graph, Figure 4, unless the stray capacity is compensated for by a reduction in the capacity of the high voltage condenser.

As a final consideration the effect of residual inductance in the instrument and its connecting leads can be calculated. If we consider the equivalent capacitive and

inductive circuit to be as shown in Figure 5:

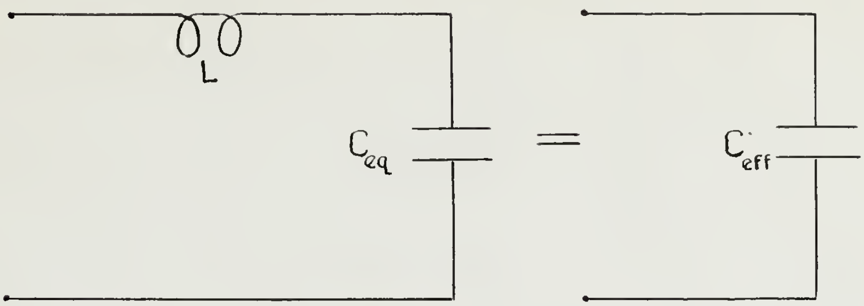

Figure 5

$$\frac{1}{j\omega C_{eff}} = j\omega L + \frac{1}{j\omega C_{eq}} = \frac{1 - \omega^2 L C_{eq}}{j\omega C_{eq}}$$

or the effective capacity of the circuit, Ceff, is given by

$$C_{eff} = \frac{C_{eq}}{1 - \omega^2 L C_{eq}} \tag{11}$$

and rearranging Equation (11) we can solve for an expression for L, the residual inductance:

$$L = \frac{1}{\omega^2 C_{eq}} \left(1 - \frac{C_{eq}}{C_{eff}} \right) \tag{12}$$

The utility of Equations (11) and (12) will be demonstrated later, in the analysis of the results of tests made on the experimental standard of power factor. It will suffice to say here that Equation (10) indicates that the effective capacity of the circuit will increase with frequency unless residual inductance is maintained at an extremely low value. Incidentally Equation (11) is identical

with that used by the General Radio Company[8] and others to calculate the effect of residual inductance in precision condensers.

POWER DISSIPATING ELEMENTS - GENERAL

In the preceeding sections of this paper it was specified that the power dissipating element of the high frequency standard of power factor would be so designed as to permit the accurate measurement of actual power. To achieve this objective considerable study and experimental work was carried out. The following were basic considerations which were considered as having to be met:

(a) Only straight or uncoiled wires of moderate length could be used to obtain the required resistance for the power dissipating element. This is necessary to keep residual inductance to a minimum.

(b) Any connecting leads or wires to the power measuring apparatus must be so arranged as to allow a minimum of coupling between the circuit ofthe standard itself and the power measuring device.

The most obvious, and probably the most satisfactory, method of determining the power dissipated in a resistance is to measure the heat developed when a current flows. It was decided to employ this basic principle in the power dissipating element.

An ideal type of power dissipating element was

proposed by Dr. C. Frank Miller, and would comprise a thin-walled metal resistor tube into which an insulated thermocouple is inserted to about mid-length of the tube from the base (or low potential) end. If an appropriate meter or galvanometer is connected across the two free ends of the thermocouple (which extend out of the tube), the deflection of this meter upon flow of current through the resistor tube will be proportional to the amount of heat generated. This is simply employing the thermo-electric force[9] in exactly the same manner in which it is employed in radio frequency ammeters that are commercially available in many types, ranging up to precision instruments costing several hundred dollars. Considering a power dissipating element of this type, the meter to the thermocouple could be readily calibrated to indicate the amount of power being dissipated in the resistor tube.

Unfortunately, simple preliminary calculations based upon nichrome as the material from which to construct the resistor tube, showed that to obtain a tube with resistance of about five ohms and of length six inches or less, the wall thickness and diameter would have to be exceedingly small. Such tubing would be difficult to procure and employ, and the power dissipating element would be very fragile.

Two methods of employing the above principle but obviating the objectional structural features of the thin

metal tube were possible.

(a) The resistor tube could be built by placing a thin metallic film on a ceramic tube, to the ends of which are fitted electrodes for connecting into the circuit of the standard. This metallic film could easily be placed on the ceramic tube by the "sputtering process"[10] or by the use of one of several chemical solutions that when applied, and baked to remove the solvent, deposit a good quality adhering film of metal.[11,12] A platinum film is believed to hold promise for this type of resistor insofar as obtaining the desired value of resistance. The junction between the electrodes and the plated ceramic tube could easily be electroplated to ensure good contact.

(b) The second adoption of the above principles, and that employed in the experimental standard of power factor, is that of replacing the resistor tube with a resistor wire which is terminated at the low potential end by a low resistance conducting tube of small (but available) size. Into this tube the thermocouple is inserted so that the junction

is located at the junction of the tube and resistor wire. By employing this method the thermocouple junction is located at a relatively "cool" point and is therefore subjected to only a sample of the maximum temperature generated. As will be shown in a following section this method proved to be completely satisfactory.

Another type of power dissipating element that is of entirely different design has shown great promise not only for use in a standard of power factor, but also for use in other applications where precision measurements of small amounts of power or current are required. This device, based upon an idea presented by Dr. John J. Chapman of the Johns Hopkins University, consists essentially of a thermometer, the liquid of which is a good dielectric, and into the bulb section of which a filament is installed in exactly the manner as is in a small light bulb. The heat generated when a current is passed through the filament is transmitted to the dielectric, causing it to expand with a consequent rise of its level in the thermometer capillary tube. The amount of rise of the level of the liquid in the capillary tube can be calibrated directly in terms of power dissipation in the filament. Preliminary experiments with this type of device indicate that it is particularly suited for use in a standard of power

factor designed to test low voltage bridges or networks.

Resistor Material Characteristics

Before proceeding with the description of the construction of the power dissipating element employed in experimental standard of power factor it is of interest to consider in more detail the characteristics to be considered in the selection of the resistor material. The study of this was made investigating the following points:

(a) Is it possible to obtain the requisite resistance combined with long life power dissipating capability without resorting to excessive lengths or configurations that will add excessive residual inductance to the circuit?

(b) What is the effect upon the operation of the standard of the variation of resistance with temperature?

(c) What will be the action of skin effect, considering the circuit as a whole?

When one considers the problem of building a power dissipating element of small size and capable of dissipating up to 200 watts or more (as is necessary in power factor standards that are to operate in the 20 to 25 kilovolt range), tungsten as a resistor material is indicated because of its

high melting point and consequent good power dissipating capacity. Any such high power element must be in an evacuated envelope, or better still, in an inert atmosphere. At the lower voltage levels, such as that for which the experimental standard of power factor was designed, nichrome is a good resistor material.

The following is a brief outline of the study made of tungsten as a resistor material, and will illustrate the investigation of the aforementioned points:

(a) Resistance and power.

The power input characteristics[10] per centimeter length of .010 inch diameter tungsten wire at 2500° Kelvin are:

Voltage	.901	volts
Current	6.18	amperes
Power	5.56	watts
Life	1650	hours

From which:

Resistance per centimeter = .146 ohms
Length necessary for 5.3 ohms = 36 centimeters
Power capacity of the above length = 200 watts

The above would yield a dissipating element capable of handling the required power. The length borders upon becoming excessive when inductive effects are considered.

(b) Variation of resistance with temperature.

Consider the generally accepted expressions

for the resistance, r , of a conductor, and the resistivity, ρ , from which it is derived:[13]

$$r = \rho \frac{\ell}{A} \quad \text{where } \ell = \text{length}$$
$$A = \text{cross sectional area}$$

$$\rho = \rho_0 [1 + \alpha_t (T_1 - T_0)]$$

where T = absolute temperature in degrees centigrade

For tungsten[13]

ρ_0 = 5.51 micro-ohm centimeters at T_0 = 20° centigrade

α_t = .0045

If we assume that when the standard is registering a power factor of .002 the temperature of the resistor is 2500° Kelvin; and by assuming temperature proportional to power, the temperature at .0002 power factor will be 250° Kelvin.

$$\frac{R_{.002}}{R_{.0002}} = \frac{\frac{\ell}{A}\rho_0 [1 + \alpha_t (T_{.002} - T_0)]}{\frac{\ell}{A}\rho_0 [1 + \alpha_t (T_{.0002} - T_0)]}$$

$$= \frac{1 + .0045 \times 2480}{1 + .0045 \times 230} = 5.89$$

where the subscripts denote quantities at .002 and .0002 power factors.

To evaluate the effect of this variation in resistance we must look into the power relationships:

$$\frac{P_{.002}}{P_{.0002}} = \left(\frac{I_{R.002}}{I_{R.0002}}\right)^2 \frac{R_{.002}}{R_{.0002}} = \left(\frac{I_{R.002}}{I_{R.0002}}\right)^2 5.89 = 10$$

or:

$$\frac{I_{R.002}}{I_{R.0002}} = \left(\frac{10}{5.89}\right)^{\frac{1}{2}} = (1.7)^{\frac{1}{2}} = 1.31$$

This indicates that a much smaller change in current through the resistor is necessary to effect a ten-fold change in power when the resistor has a large temperature coefficient of resistivity than would be necessary if the resistance remained constant (in which case the current ratio would be $\sqrt{10} = 3.18$). This is very desirable in that it makes necessary a smaller variation in capacity of the shunting condenser, C_2, to effect a given change in power factor of the standard.

(c) Skin effect.

In this qualitative discussion of skin effect it will be assumed that the standard is being employed at one particular frequency and that its power factor is being varied from .002 to .0002, as before.

The effective high frequency resistance of a wire depends upon the parameter:[15]

$$\alpha_f = \frac{\omega\mu\sigma\mu_0 a^2}{4}$$ where μ = permeability
σ = conductivity
a = radius of the wire
$\omega = 2\pi f$

From the preceeding discussion on the effect of temperature on resistance

$$\frac{R_{.002}}{R_{.0002}} = \frac{\frac{1}{\sigma_{.002}}}{\frac{1}{\sigma_{.0002}}} > 1$$

or

$$\frac{\sigma_{.002}}{\sigma_{.0002}} < 1$$

In the case where α_f is large the effective resistance varies as $\left(\frac{\alpha_f}{2}\right)^{\frac{1}{2}}$ times the direct current resistance.[15] Therefore considering the ratio of effective resistances it is seen that this will be the ratio of the direct current resistances multiplied by the square root of the ratio of the conductivities, that is:

$$\frac{R_{eff\ .002}}{R_{eff\ .0002}} = \frac{R_{.002}}{R_{.0002}} \frac{\left(\frac{\omega\mu\sigma_{.002}\mu_0 a^2}{4}\right)^{\frac{1}{2}}}{\left(\frac{\omega\mu\sigma_{.0002}\mu_0 a^2}{4}\right)^{\frac{1}{2}}} = \frac{R_{.002}}{R_{.0002}}\left(\frac{\sigma_{.002}}{\sigma_{.0002}}\right)^{\frac{1}{2}}$$

at a particular frequency.

But it was previously shown:

$$\left(\frac{\sigma_{.002}}{\sigma_{.0002}}\right) < 1$$

Therefore we see that skin effect tends to offset the desirable increase in resistance with increasing temperature. This may, however, be a beneficial effect, because, suppose due to the temperature effect:

$$\frac{I_{R,.002}}{I_{R,.0002}} \longrightarrow 1$$

We would have a situation where we could not set the standard to provide a definite desired value of power factor. It would still indicate correctly, but it would theoretically select its own power factor to simulate.

DETAILS AND TEST OF THE POWER DISSIPATING ELEMENT

As was stated previously, the power dissipating element employed in the experimental standard of power factor is of the thermocouple - resistor wire type. The immediate availability of nichrome wire dictated this as the material from which to construct the resistor. A sketch showing the essential details of this element is shown in Figure 6.

The data on the wire from which the resistor was made is given below:[14]

Manufacturer: Wilber B. Driver Company,
Newark, New Jersey

Trade name of wire: "Tophet C"

Size: Number 33 (.0071 inches in diameter)

Resistance: 13.39 ohms per foot at 20° Centigrade

Current versus temperature and resistance characteristics:

Degrees C. :	20	100	200	300	400	500	600	700
Amperes :		.432	.565	.715	.900	1.03	1.19	1.39
Resistance multiplying factor :	1.000	1.019	1.043	1.065	1.085	1.093	1.110	1.114

(continued)

Degrees C. :	800	900	1000
Amperes :	1.63	1.81	2.10
Resistance multiplying Factor :	1.123	1.132	1.143

POWER DISSIPATING ELEMENT
EXPERIMENTAL STANDARD OF H.F. POWER FACTOR

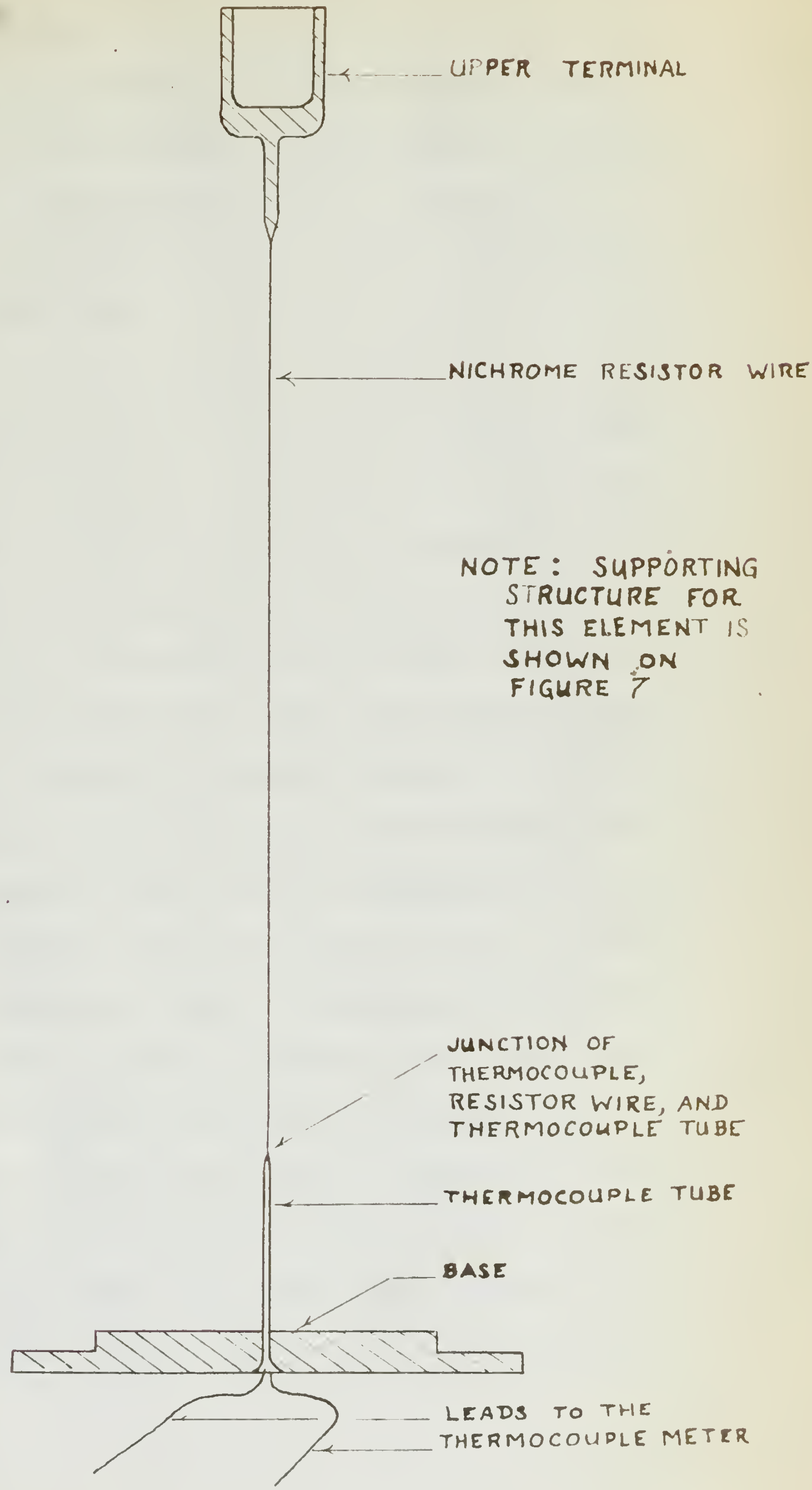

FIGURE 6

The wires comprising constantin-chromel thermocouple were insulated from each other and from the thermocouple tube (except at the junction) by bakelite varnish which was applied by dipping and then baked as prescribed for the specific insulating material. Tests after installation of the thermocouple indicated that the insulation was satisfactory.

Before this power dissipating element could be considered satisfactory for use in the standard of power factor, it was necessary to determine if the "sample" of temperature rise above room temperature subjected to the thermocouple junction when current heated the resistor wire would vary with conditions at the base. (Such as base being in contact with a good or poor heat conductor, etc.). The effect of air currents varying the equilibrium temperature attained by the resistor is eliminated by the fact that the element would be completely enclosed in a metal electrical shield when installed in the standard.

Tests were made to determine the effect of the different base arrangements mentioned above. The power dissipating element was enclosed in a temporary metal shield that extended from the base to a point about two inches above the upper terminal, and the base in turn was placed on two metal blocks. Good metallic contact was ensured between the base and shield and between the base

and metal supporting blocks. The following conditions were imposed, during which readings of a thermocouple meter were taken when current heated the wire:

(a) With the element situated as described above.

(b) With the shield and blocks thermally insulated from the base by 3/32" cork insulation.

(c) With good metallic contact between the shield, base, and blocks, and the base blocks surrounded by melting ice.

The results of these tests are given in Table III. Before any set of readings was taken the apparatus was allowed to reach an equilibrium condition; the thermocouple meter was then set to zero deflection position and current applied to the circuit. Between individual readings the apparatus was allowed to return to its equilibrium condition, and in a few cases it was necessary to "rezero" the meter. Direct current was employed to provide the power input, and the polarity of the voltage applied to the upper terminal is indicated in the tabulated results. For low values of power input a wall galvanometer was used as the thermocouple meter, and at higher powers a Unipivot portable galvanometer was employed. This latter instrument is satisfactory over the power range (2 to 18 watts) for which

the power dissipating element was designed, and it is of small size and convenient to transport and use.

Table III

Results of the Base Condition Tests of the Experimental Standard of High Frequency Power Factor

Test A - With good metallic contact between the base, shield, and supporting blocks

Meter - Leeds and Northrup wall galvanometer

Voltage	Amperes	Watts	Meter Deflection	Watts/Unit Def.
+1.45	.26	.377	3.12	.1210
+1.45	.26	.377	3.10	.1216
+1.45	.26	.377	3.10	.1216
+1.45	.26	.377	3.15	.1197
+1.45	.26	.377	3.12	.1210
+1.45	.26	.377	3.10	.1216
+1.45	.26	.377	3.08	.1223
+1.45	.26	.377	3.12	.1210
Averages		.377		.1212

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.1212-.1197}{.1212} = 1.24\%$$

Test B - Conditions the same as Test A except the polarity of the voltage was reversed.

Voltage	Amperes	Watts	Meter Deflection	Watts/Unit Def.
-1.45	.26	.377	2.88	.1310
-1.45	.26	.377	2.85	.1323
-1.45	.26	.377	2.91	.1295
-1.45	.26	.377	2.92	.1291
-1.45	.26	.377	2.90	.1300
Averages		.377		.1304

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.1323-.1304}{.1304} = 1.46\%$$

Test C - Conditions the same as Test B

-4.29	.730	3.138	22.32	.1403
-4.30	.725	3.118	21.80	.1430
-4.29	.725	3.110	21.70	.1433
-4.25	.720	3.060	21.50	.1423
-4.24	.725	3.077	21.45	.1433
-4.25	.722	3.070	21.32	.1440
-4.24	.715	3.030	21.20	.1430
Averages		3.085		.1427

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.1427-.1403}{.1427} = 1.68\%$$

During Test C it was noted that the power source (3 dry cells) was inadequate to maintain steady voltage and current during the time required to take readings. It was considered that Test C was questionable, and Test D, under the same conditions was made using six batteries.

Test D - Conditions the same as Test B

-4.40	.74	3.256	22.25	.1461
-4.40	.74	3.256	22.30	.1459
-4.40	.74	3.256	22.30	.1459
-4.39	.74	3.248	22.30	.1457
-4.38	.74	3.240	22.30	.1452
Averages		3.251		.1458

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.1458-.1452}{.1458} = .41\%$$

<u>Test E</u> - With good metallic contact between the base, shield, and supporting blocks.

Supporting blocks in melting ice.

Meter - Leeds and Northrup wall galvanometer

-4.38	.74	3.241	22.40	.1448
-4.38	.74	3.241	22.30	.1452
-4.37	.74	3.237	22.20	.1458
-4.37	.74	3.237	22.30	.1450
-4.37	.74	3.237	22.30	.1450
-4.37	.74	3.237	22.30	.1450
-4.34	.73	3.170	21.90	.1448
-4.34	.73	3.170	22.10	.1423
-4.32	.73	3.150	22.10	.1425
Averages		3.213		.1446

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.1446-.1425}{.1446} = 1.45\%$$

<u>Test F</u> - Conditions the same as Test E

Meter - Unipivot portable galvanometer

-8.25	1.34	11.07	19.1	.579
-8.20	1.335	10.94	19.0	.576
-8.15	1.33	10.82	19.0	.570
-8.10	1.32	10.69	18.5	.578
Averages		10.88	18.9	.576

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.576-.570}{.576} = 1.04\%$$

<u>Test G</u> - With good metallic contact between the base, shield, and supporting blocks. (Melting ice removed)

Meter - Unipivot portable galvanometer.

-8.2	1.34	10.99	19.2	.572
-8.12	1.34	10.72	19.0	.564
-8.12	1.32	10.72	18.6	.576
-8.10	1.315	10.65	18.5	.576
-8.04	1.31	10.53	18.4	.573
Averages		10.72	18.7	.572

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.572-.564}{.572} = 1.4\%$$

Test H - With cork thermally insulating the base from the shield and the supporting blocks.

Meter - Unipivot portable galvanometer

-8.03	1.31	10.52	18.5	.569
-8.00	1.31	10.49	18.4	.570
-8.00	1.31	10.49	18.3	.573
-8.00	1.295	10.37	18.2	.569
-7.94	1.29	10.24	18.0	.569
Averages		10.42	18.3	.570

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.573-.570}{.570} = .53\%$$

Test I - Conditions and meter the same as Test H.

-7.92	1.29	10.21	18.4	.555
-7.90	1.28	10.12	18.1	.558
-7.87	1.28	10.08	17.9	.563
-7.83	1.275	9.99	17.9	.558
-7.80	1.27	9.91	17.8	.556
Averages		10.06	18.02	.558

$$\frac{\text{Maximum Deviation from Average}}{\text{Average Watts per Unit Deflection}} = \frac{.563-.558}{.558} = .9\%$$

While the results of the above test indicate that the power dissipating element is perfectly satisfactory for use in the standard of power factor, it is of interest to examine some of the results more closely:

(a) A comparison of the averages of Test D with those of Test E makes it appear that the melting ice around the base lowered the average watts per unit meter deflection. However, in the tests at a higher power level, Tests F and G, the effect is reversed. It therefore can be concluded that the ice condition at the base is not responsible for the observed variations. A more likely conclusion is that the number of readings taken in each test is insufficient to obtain a true average and that the differences are due to reading errors, etc.

(b) The results of Tests G and H indicate that the effect of thermal insulation is negligible.

(c) The differences in the average watts per unit meter deflection between Tests A and B, and between Tests H and I, show definitely that the polarity of the direct

current voltage has an effect. This had also been noted on earlier trials of the element and is attributed to the voltage drop along the weld at the junction of the thermocouple and thermocouple tube. This voltage drop appears in the thermocouple circuit. This same effect had been observed to a very pronounced degree in an experiment with a power dissipating element in which the tube formed one part of the thermocouple; while at the same time performed the same function as in this element of being the termination of the resistor wire. Also in a test in which the thermocouple was electrically insulated from the tube at all points the change of polarity of direct current voltage had no effect (but the instrument was much less sensitive). It is to be expected that no trouble should be experienced from the above with alternating current.

(d) The percentages of maximum deviation from the average of the watts per unit deflection is in all cases acceptably small. The variations in the average watts per unit deflection as the power level was changed might indicate a small change with power.

The data and the description concerning the actual calibration of this power dissipating element are included in the section of this paper concerning the calibration of the standard of power factor as a whole. It will suffice to say here that the agreement with which the results of Tests F, G, H, and I of this section fitted the actual calibration curve were most pleasing.

CONSTRUCTION AND CALIBRATION OF THE EXPERIMENTAL STANDARD OF HIGH FREQUENCY POWER FACTOR

In this section will be described the details of the various components of the experimental standard and their assembly into the completed instrument. The calibrations that were carried out and the results of these calibrations are also included here. A cross-sectional drawing of the assembled device is shown as Figure 7, to enable the reader to obtain an accurate picture of the structural and operational features. Inasmuch as the power dissipating element was adequately discussed in the preceeding section, this component (except for its calibration) will be only briefly treated.

The High Voltage Condenser, C_1

A vacuum variable condenser manufactured by the Jennings Radio Manufacturing Company, San Jose, California, was obtained for use as the high voltage condenser. The variation in the capacity of this element is obtained by varying the separation of two cup-shaped "plates" by means of a micrometer-type capacity adjuster extending downward from the end of the lower terminal. This condenser is enclosed in an evacuated glass envelope (the outline of which is shown in Figure 7), at opposite ends of which are located the connecting terminals. Such a terminal arrangement is considered ideal for use in the standard of power factor, in that it

EXPERIMENTAL STANDARD OF H.F. POWER FACTOR

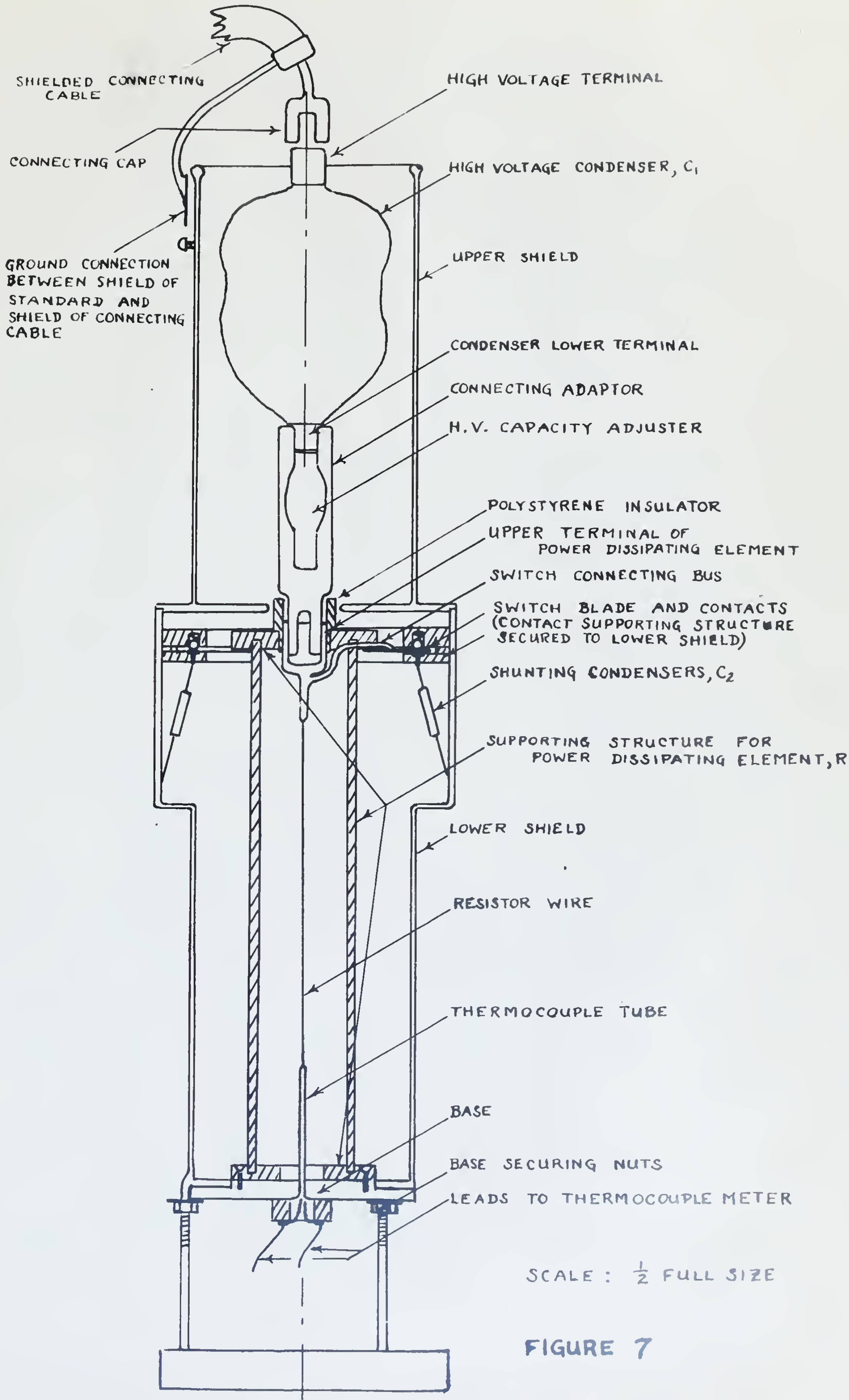

FIGURE 7

provides a straight path for current flow through the unit.

Manufacturer's data:

Type:	"T"
Serial number:	C-208
Maximum capacity:	27.2 micromicrofarads
Minimum capacity:	5.0 micromicrofarads

When tested in the Twin-T Impedance Measuring Network (General Radio Company), this condenser exhibited undetectable conductance, a condition that is mandatory for use in this application.

This high voltage condenser is electrically connected to the upper terminal of the power dissipating element by means of the connecting adaptor which fits around the micrometer-type adjuster and clamps to the condenser lower terminal. This connecting adaptor also serves as the sole structural support for the high voltage condenser.

The Power Dissipating Element, R

The thermocouple-resistor wire power dissipating element, the details of which are also depicted in Figure 7, makes connection to the lower end of the connecting adaptor. The heater wire and the upper terminal of this element are rigidly supported with respect to the base by the non-conducting supporting structure shown in the figure.

The Shunting Condensers, C_2

To provide variation in the value of shunting capacity paralleling the power dissipating element, it was

decided to incorporate in the instrument a switching arrangement whereby selected values of fixed capacitance covering the range indicated by the design graph, Figure 4, could be inserted into the electrical circuit without disassembly of the standard. Five 1000 micromicrofarad and three 500 micromicrofarad commercial silver-mica condensers were used to build up this variable capacitance.

The Shunting Condenser Switch

This device is comprised of a switch blade made in the form of a 165 degree sector which is rigidly fastened to the upper part of the supporting structure for the power dissipating element, and a set of ten contacts mounted in an insulated supporting structure, also covering a 165 degree sector, attached to the inside of the lower shield. Electrical connection between the switch blade and the upper terminal of the power dissipating element is made by the switch connecting bus. The shunting condensers are installed between the terminals of the switch contacts and the shield as shown in Figure 7. Operation of the switch is achieved by loosening the base securing nuts and rotating the base with respect to the shield. Turning the base thus, rotates the power dissipating element, the high voltage condenser, and the switch blade, and causes the switch blade to make connection with an increasing number of switch contacts thereby paralleling an

increasing number of the shunting condensers with the power dissipating element. Around the circumference of the base are engraved ten switch positions which when aligned with an index line on the lower shield indicate:

Switch Position	C_2 in Micromicrofarads
1	1000
2	1500
3	2000
4	2500
5	3500
6	4500
7	5500
8	6500
C	0 (Switch open)
S	Power dissipating element is short circuited

The "C" switch position (switch open) is normally used when calibrating the power dissipating element, as will be explained later.

The Shield

The circuit of the experimental standard of power factor is enclosed in a cylindrical brass shield which is made in two sections, labeled the upper and lower shields in Figure 7. The purpose of making the shield in two sections was solely for ease in assembling the standard. Good electrical contact is insured between the base and the lower shield, and between the lower and upper shield by close-fitting machined surfaces which are held together by securing devices. It is to be noted that stray capacity between

the shield and upper plate and terminal of the high voltage condenser will be an additive quantity to the equivalent capacity of the circuit. On the other hand stray capacity between the lower terminal of the high voltage condenser, adaptor, switch blade, etc., and the shield, will only be additive to the shunting capacity.

Calibration of the Power Dissipating Element

For calibration of the power dissipating element, the standard was completely assembled as shown in Figure 7. The switch was set to the "C" position on which setting there is no shunting capacity paralleling the resistor wire. Connecting leads were run from a calibrating terminal on the switch blade and from the base to the meters and the power source, which was the regular 60 cycle, 110 volt supply reduced by a transformer and a variac. The Unipivot galvanometer was employed as the thermocouple meter.

A schematic diagram of the meter connections is shown in Figure 8, below:

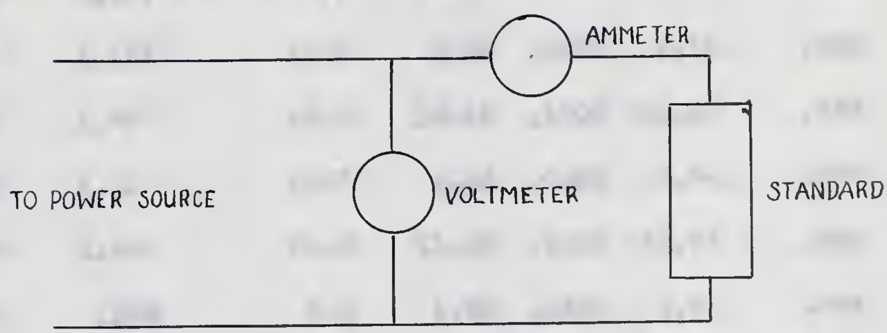

Figure 8

The ammeter resistance was listed on the instrument as .2824 ohms.

The data obtained is tabulated in Table IV, and is shown plotted as the Power Calibration Curve for the standard in Figure 9. In addition, the values obtained when the Unipivot galvanometer was used in the base conditions test of the power dissipating element are plotted in Figure 9. These points show close agreement with the 60 cycle alternating current calibration.

<u>Table IV</u>

Power Calibration Data for the Experimental Standard of High Frequency Power Factor

Volts(V)	Amperes(I)	Deflection	VI	I^2R_{am}	Watts	$\frac{\text{Watts}}{\text{Unit Def.}}$
9.78	1.497	25.1	14.63	.1135	14.51	.578
9.88	1.512	26.1	14.94	.1207	14.82	.568
9.94	1.52	26.3	15.12	.1213	15.00	.570
4.63	.74	6.0	3.43	.0580	3.37	.562
5.11	.816	7.0	4.16	.0650	4.095	.584
5.01	.805	7.2	4.04	.0643	3.98	.552
7.25	1.127	14.7	8.16	.0900	8.07	.555
7.25	1.136	14.6	8.25	.0907	8.16	.560
8.10	1.25	18.0	10.13	.1000	10.03	.572
7.80	1.21	16.7	9.44	.0965	9.34	.560
8.60	1.32	20.0	11.35	.1054	11.24	.562
3.30	.545	3.0	1.80	.0435	1.76	.585
3.92	.637	4.1	2.50	.0509	2.45	.596

4.60	.775	6.8	3.78	.0587	3.72	.564
5.40	.857	7.9	4.025	.0684	4.56	.577
6.26	.975	10.7	6.10	.0778	6.02	.563
6.83	1.062	12.9	7.32	.0855	7.23	.561
7.11	1.102	14.2	7.84	.0881	7.75	.545
7.60	1.181	16.0	8.97	.0942	8.88	.555
8.00	1.241	17.9	9.93	.0990	9.83	.550
8.43	1.300	19.2	10.97	.1040	10.87	.566
8.89	1.361	21.5	12.10	.1087	11.99	.563
9.22	1.421	23.0	13.20	.1134	13.09	.569
9.69	1.478	24.6	14.33	.118	14.21	.578
9.76	1.488	25.3	14.57	.119	14.45	.573
10.02	1.526	26.6	15.30	.122	15.18	.571
9.35	1.427	22.8	13.35	.1140	13.24	.582
8.73	1.345	20.2	11.74	.1072	11.63	.576
7.22	1.122	14.0	8.10	.0895	8.01	.573
6.37	.992	11.0	6.32	.0792	6.24	.567
5.10	.807	7.0	4.11	.0642	4.05	.578
4.54	.721	6.0	3.275	.0575	3.22	.537
4.00	.644	4.6	2.58	.0514	2.53	.550
3.52	.575	3.4	2.02	.0469	1.98	.579
3.01	.48	2.1	1.445	.0383	1.41	.669
2.50	.41	1.5	1.025	.0327	.99	.661
1.99	.30	.8	.597	.0240	.57	.718

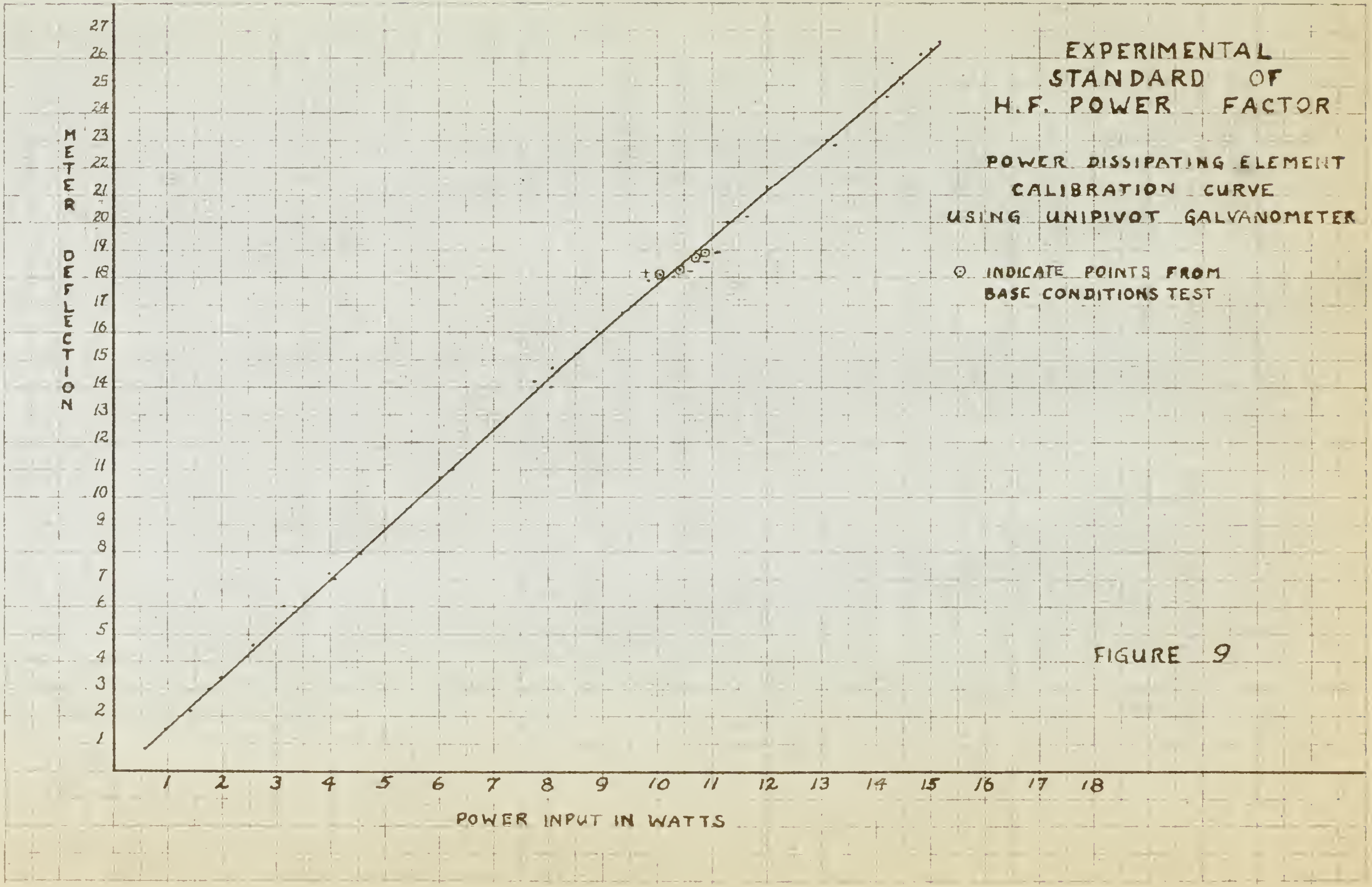
EXPERIMENTAL
STANDARD OF
H.F. POWER FACTOR
POWER DISSIPATING ELEMENT
CALIBRATION CURVE
USING UNIPIVOT GALVANOMETER
⊙ INDICATE POINTS FROM
BASE CONDITIONS TEST
METER DEFLECTION
27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18
POWER INPUT IN WATTS

FIGURE 9

The Effective Capacity Calibration and Determination of the Residual Inductance of the Standard

The tests to determine the effective capacity, Ceff, of the high frequency standard of power factor were made employing a Type 160-A Q Meter manufactured by the Bontoon Radio Corporation, Boutoon, New Jersey. This instrument was used in the prescribed manner for measuring the capacity of small condensers, that is: The instrument was first tuned with the connecting leads in place but the standard of power factor removed, and then retuned after connecting the standard to the leads. The difference in the setting of the Q Meter tuning condensers to effect the above retuning is then a direct measure of the effective capacity of the standard (within the limits of accuracy of the Q Meter). The high voltage condenser in the standard was set to its minimum value of capacity and readings were taken with the switch set at various values of shunting capacity, C_2, and at various frequencies.

Three distinct effective capacity measuring tests were made with this meter:

(a) With the shielded connecting lead connected as indicated in Figure 7, but the lead shield grounded only at the Q Meter. The shield of the standard of power factor was grounded to the Q Meter by a bus attached to

the base of the standard.

(b) With the shielded connecting lead attached, and the lead shield forming the ground connection between the top of the shield of the standard and the Q Meter, as shown in Figure 7.

(c) With the connections the same as those described in subparagraph (b), above, but retuning the Q Meter with the vernier tuning condenser only, after insertion of the standard of power factor. The reason for this test will be discussed in a following paragraph.

The results of the test with connections as outlined in the preceeding subparagraph (a), indicated a variation in effective capacity of the standard from 7.1 micromicrofarads at a frequency of ten megacycles per second to 13.8 micromicrofarads at thirty megacycles. This test was definitely unsatisfactory from the point of view of acceptability of the standard of power factor. The reason for this radical variation in the effective capacity was strongly suspected to be caused by residual inductance. The loop formed by the connecting leads in this test was relatively large.

The connections used for the second testing of the standard radically reduced the size of the loop formed by the

connections, and the results were much more favorable. Table V(a) shows the data obtained in this test.

Table V(a)

Effective Capacity Calibration Data for the

Experimental Standard of High Frequency Power Factor

Frequency in megacycles per second	Effective capacity in micromicrofarads (Averages of a number of readings)
8	7.06
9.5	7.04
11	7.12
12	7.02
13	7.03
14	6.92
15	7.00
16	7.07
17	7.20
18	7.20
22	7.24
23	7.18
24	7.23
26	7.38
27	7.40
28	7.62
30	7.85

While the above results were definitely more satisfactory from the point of view of overall variation in the effective capacity, the variation from frequency to frequency when plotted showed undesirable variations which should be accounted for. It was realized that the variations in question are in the order of magnitude of the listed accuracy of the Q Meter,[2] and a manipulation of the meter tuning condenser dials at the 18 megacycle frequency setting

(with the standard of power factor connected) indicated that about a one-fifth micromicrofarad variation in capacitance reading would occur at two different settings of the main tuning dial within the six micromicrofarad range of the vernier tuning condenser. A further check indicated that the range of the vernier tuning condenser on the Q Meter could be extended to a little over seven micromicrofarads with reasonable accuracy. The third test was then conducted at the lower frequencies where the previous test indicated that the effective capacity ofthe standard was within the range of the Q Meter vernier condenser, with the following results:

Table V(b)

Frequency in megacycles per second	Effective capacity in micromicrofarads (individual readings)
8	6.98
9	6.95
10	6.98
11	6.96
12	7.04
13	7.05
14	7.08

At no time during the tests was there a consistent detectable difference in the measured effective capacity of the standard of power factor with different values of shunting capacity paralleling the power dissipating element. This agrees with the results of the mathematical analysis

wherein it was shown that the differences in the equivalent capacity expected with different values of shunting capacity are of very small order of magnitude.

The results of the foregoing tests are plotted as the Effective Capacity Calibration Curve for the Experimental Standard of High Frequency Power Factor, Figure 10.

Determination of Residual Inductance and the Calculated Effective Capacity.

The increase in the effective capacity with frequency, as shown in the mathematical analysis of the basic circuit, can be accounted for by the action of residual inductance in the circuit. It is considered that the difference in the results of the first two effective capacity measuring test justify the assumption that the increase in effective capacity with frequency is caused by this quantity. If we employ Equation (12):

$$L = \frac{1}{\omega^2 C_{eq}}\left(1 - \frac{C_{eq}}{C_{eff}}\right) \qquad (12)$$

and from a study of the capacity curve obtained by test on Figure 10, assume:

C_{eff} = 7.75 micromicrofarads at a frequency of 30 megacycles per second.

C_{eq} = 6.30 micromicrofarads

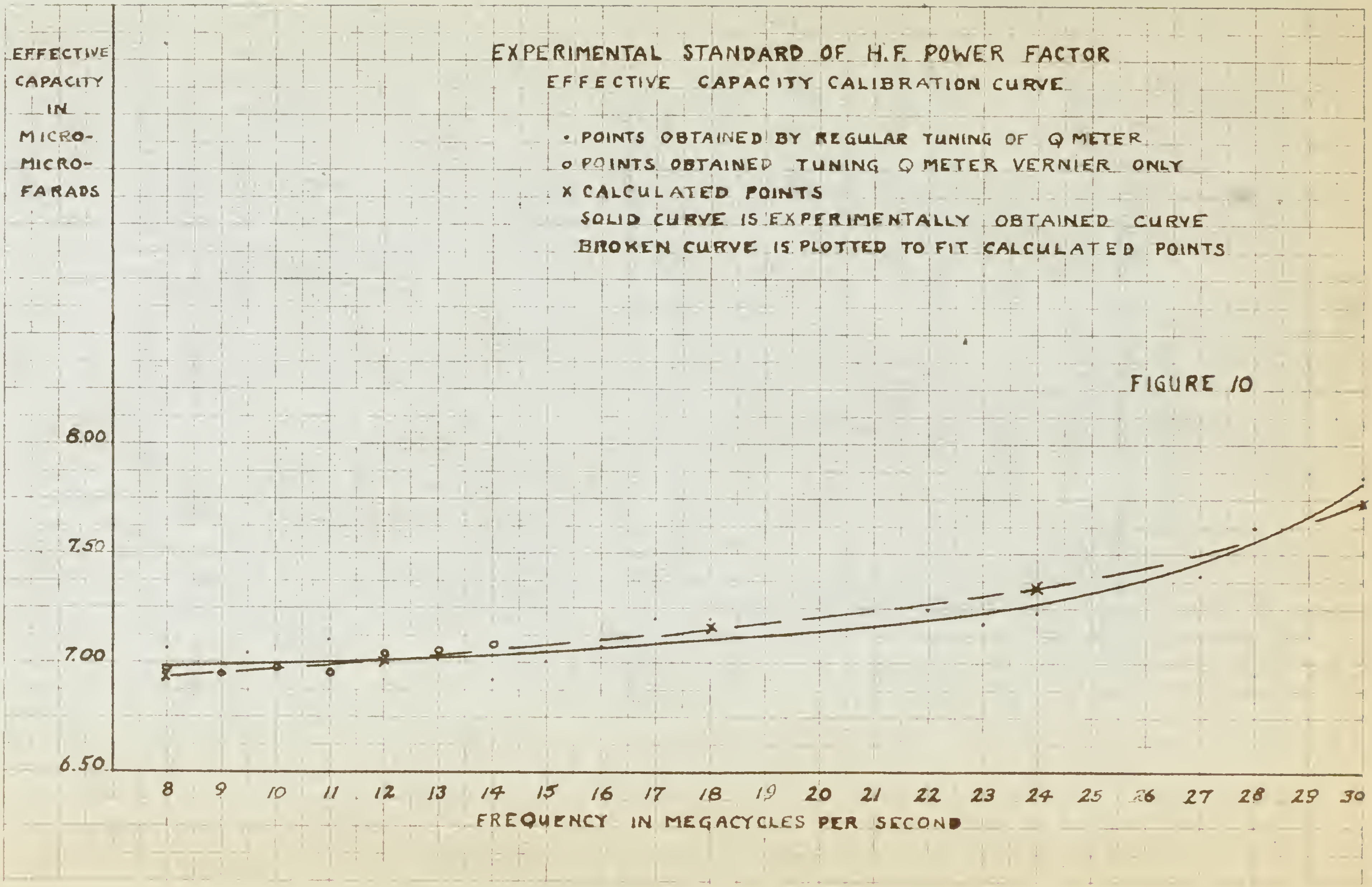
EXPERIMENTAL STANDARD OF H.F. POWER FACTOR
EFFECTIVE CAPACITY CALIBRATION CURVE
• POINTS OBTAINED BY REGULAR TUNING OF Q METER
o POINTS OBTAINED TUNING Q METER VERNIER ONLY
x CALCULATED POINTS
SOLID CURVE IS EXPERIMENTALLY OBTAINED CURVE
BROKEN CURVE IS PLOTTED TO FIT CALCULATED POINTS
EFFECTIVE CAPACITY IN MICRO-MICRO-FARADS
8.00
7.50
7.00
6.50
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
FREQUENCY IN MEGACYCLES PER SECOND

FIGURE 10

Solving Equation (12) for the residual inductance, L, it is found

$$L = .45 \text{ microhenries}$$

To verify the above solution for the residual inductance it is only necessary to solve Equation (11):

$$C_{eff} = \frac{C_{eq}}{1 - \omega^2 L C_{eq}} \qquad (11)$$

(using the above values of Ceq and L) for the calculated effective capacity at a few points over the frequency range of the instrument. Table VI gives the results of these calculations.

Table VI

Calculated Effective Capacity of the

Experimental Standard of High Frequency Power Factor

Frequency in megacycles per second	Effective capacity in micromicrofarads
6	6.95
12	7.02
18	7.19
24	7.34
30	7.75

The foregoing results are also plotted on the calibration chart, Figure 10. Although it is considered that the experimentally determined curve follows the curve obtained by calculation fairly well throughout the frequency range, the almost perfect correlation of the

points obtained in the frequency range of 8 to 14 megacycles, when only the vernier tuning condenser was employed on the Q Meter, is particularly pleasing.

Considering everything, it is believed that the calibration curve obtained in the foregoing tests is fairly accurate. However, for the sake of precision a further calibration, or affirmation of the curve of effective capacity, Figure 11, with a more precise instrument than the Q Meter, is desirable.

Method of Use of a Standard of High Frequency Power Factor

To test the accuracy of a circuit that is used in measuring dielectric power factors, the standard must be connected into the circuit in lieu of the dielectric and its electrodes. The regular operating procedure for the circuit should be carried out as is used in measuring dielectric properties, with the standard simulating a dielectric sample to be tested. The accuracy of the circuit under test is then determined by a comparison of the power factor of the standard as indicated by the measuring circuit, and the actual value of this quantity as known from the power and capacitance calibration of the standard.

As an example, consider verifying by means of a standard the power factor measured by the circuit developed by Damianski, Witt, and Chapman.[6] This circuit operates on the phenomenom of tuning a parallel combination

of inductance and capacitance to resonance. The tuning is accomplished by means of a variable precision condenser, first, without the sample connected across the parallel circuit, and second, with the dielectric specimen shunting the above tank circuit. The difference in the capacity value of the tuning condenser to effect the two tunings of the circuit is a direct measure of the capacitance of the sample. The current that flows through the circuit each time it is tuned to resonance is measured, and from the difference of these two values of current the conductance of the dielectric specimen is easily calculated. The current measuring apparatus is connected between the low voltage junction of the parallel inductance and capacitance, and ground. For insertion into this circuit, the dielectric sample is mounted between an upper and a lower plate electrode, and surrounding this lower electrode (and in contact with the sample) is a guard ring which is maintained at ground potential.

As is obvious from the foregoing, to test this circuit a three electrode type of standard previously mentioned would be employed. The upper and lower (base) terminals of the standard would be connected across the parallel tank circuit in place of the dielectric sample, and the shield of the standard would be grounded in the same manner as is the guard ring. The accuracy of the

circuit would then be determined by comparing the power factor of the standard as indicated by the measuring circuit, with the power factor actually exhibited by the standard under the resonance condition imposed with it connected into the circuit.

CONCLUSIONS

The standard of high frequency power factor that has been built verifies the basic theory upon which it was conceived. It has been repeatedly referred to throughout this paper as "experimental", and perhaps the intended meaning of this word should be amplified. The standard herein described is experimental in that it is the first completed device, and as is the case with practically every first model, the way is pointed for an improved design. Happily in this case, little change in original concepts are indicated. This completed standard was constructed with care, and with as much attention to selection of the correct type of components as the availability of material and time permitted.

Following the above trend of thought it is considered that a large part of the value ofthis paper will lie in pointing the way to the construction of the more perfect standard of high frequency power factor, although no reason is seen why the experimental model available will not do a satisfactory job in the voltage level for which it was constructed.

A reduction in the residual inductance of the standard is probably the "number one" consideration for improvement. This can be achieved by reducing the overall length of the circuit, to wit: Obtain, or have specially

built, a high voltage condenser with the minimum possible length of connecting electrodes to the plates, and so designed that the adapter can be eliminated. The length of this same type of power dissipating element can be greatly reduced, while still maintaining sufficient power dissipating capability by the use of tungsten in the resistor wire. Furthermore there are other types of power dissipators employing the same basic idea -- for example, Dr. Chapman's thermometer type.

The other considerations for the ultimate standard can be grouped under the common heading of making it adaptable to all requisite uses and potential levels. It is very easy to foresee a standard of this type so mechanically constructed as to permit the easy insertion of a shield insulator at the low potential end to make it available for use in a three terminal network. In the experimental standard the power dissipating element does not permit easy replacement. This feature can be improved upon to the point where an assortment of power units are available for ready and quick insertion into the standard, each with its specific range of frequencies and power levels for which it will cause the standard to provide known power factors.

It is considered that by incorporating the foregoing suggestions, a high quality precision standard of high

frequency power factor, adaptable to many conditions, can be built based upon the theory and techniques presented in this paper.

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VITA

Widmer Case Hansen was born on August 1, 1913, in Fort Benton, Montana. He attended various country grammer schools in northern Wyoming, and completed his grade school and high school education in Midwest, Wyoming. On March 6, 1931, he enlisted in the U. S. Navy where he received a three months specialized training in aviation mechanics, upon the termination of which he served as a seaman in the deck force aboard the U.S.S. Wright, U.S.S. Sacramento and U.S.S. Saratoga. In 1933, upon completing the Naval Academy Preparatory Course, Hansen passed the entrance examinations to the U.S. Naval Academy, and entered the academy under the fleet quota of appointments. Graduating from Annapolis in 1937 brought him a commission in the Navy, where he has served since in the normal succession of ranks for his class. As a commissioned officer he, by his own choice, has spent much of his time in shipboard gunnery assignments. During World War II he served in the U.S.S. North Carolina for four years, and following a years tour of duty as Gunnery Officer of the U.S.S. Wyoming, he was selected, in 1948, for graduate ordnance engineering training. This assignment, the last two years of which have been spent at the School of Engineering, The Johns Hopkins University, is about to terminate.